Photonic Sensors (2011) Vol. 1, No. 2: 118–139

DOI: 10.1007/s13320-011-0027-2 **Photonic Sensors**

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Optical Fiber Sensors: a Route From University of Kent to Portugal

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Abstract: In this work the authors first summarily describe the main topics that were the subject of their post-graduate activity in fiber sensing at the Applied Optics Group of University of Kent in the late 1980s and early 1990s. After their return to Porto, Portugal, the know-how acquired during their stay at Kent and the collaboration paths that followed between the University of Porto and University of Kent were instrumental in the start-up and progress of optical fiber sensing activity in Portugal. The main topics addressed in this field, the description of some of the relevant developments achieved in recent years, the present situation and the guidelines for the future research and development activity in Portugal in fiber sensing will be the core of this work.

Keywords: Fiber optic sensors, fiber Bragg gratings, fiber sensing multiplexing

1. Introduction

The University of Kent throughout its Applied Optics Group headed by Prof. David Jackson was considered in the eighties and nineties of last century, one of the world top research centers in fiber optic sensing. A subject initially derived from the optical fiber communication endeavor but that soon followed its own driving force, essentially associated with the intrinsic favorable characteristics of this sensing technology. At a basic level, this results from the fact we are dealing with an optical field as well as, the unique characteristic of the optical fiber, which is simultaneously a communication channel and a sensing element. This feature means that no dedicated telemetry and power channels are required. This led to the evolution of remote sensing and, in principle, multi-point measurement supported by a single optical fiber feasible.

This status of University of Kent in fiber sensing made it attractive for students wanting to do post-graduate studies in this subject. It was the case of the authors of this text, that, in the previous contacts between Prof. David Jackson and Prof. António Pereira Leite, of Physics Department of University of Porto, and arrangements were made (in 1988) for J. L. Santos to undertake a PhD programme with alternate research and development (R&D) work periods in Kent and in Porto, and in 1990 for A. B. Lobo Ribeiro to undertake a MSc programme, followed by a PhD with the same conditions as J. L. Santos. The next section summarizes the topics addressed by the authors during their post-graduation studies at the University of Kent, followed by a section that

Received: 18 October 2010 / Revised version: 2 November 2010

presents the guidelines and some of the results obtained in the context of the establishment and progress of the optical fiber R&D activity in Portugal.

2. "Incubation" period

The unusual title of this section emphasizes the importance of the training at the post-graduation level of the authors in the Applied Optics Group of the Physics Department of University of Kent. The following paragraphs summarize the main research topics addressed by them in that period.

Initially research focused on the application of techniques for the stabilization of the light propagating in single mode fibers to optimize the operation of electronic speckle pattern interferometry (ESPI) systems incorporating optical fibers [1]. The PhD research programme of J. L. Santos was strongly focussed on optical fiber sensor multiplexing and signal processing, at the time a hot R&D topic. In the first study, multiplexing solutions investigated and described in the literature were compared and their most significant characteristics were evaluated, considering factors such as the topology of the network and methods of sensor addressing, network power budget and existence of intrinsic crosstalk between sensors, types of sensors and techniques of modulation/demodulation. After this study, a multiplexing approach based on time addressing was studied in which the sensors were Michelson interferometers integrated into a tree topology, a structure that was later tested to measure three phases of electrical power distribution network [2].

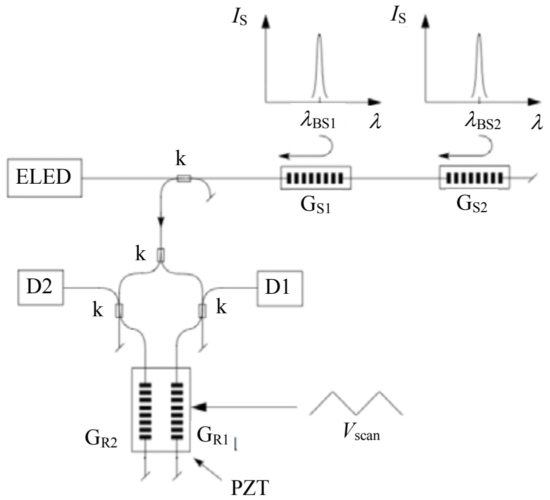
Following the proposed research line, a multiplexing layout with hybrid processing was investigated where the main novelty was the form in which the concept was implemented. Groups of interferometric sensors (Mach-Zehnder) were addressed in time; inside each group, frequency addressing was used. The sensors were distributed in a transmissive ladder topology. Frequency addressing of the sensors inside each group was performed combining ramped modulation of the injection current of a semiconductor laser with appropriate path-imbalances in the interferometers; time addressing of the group of sensors was implemented via sampling of the ramp signal, combined with the insertion of delay lines with appropriate length, distributed along the network [3].

Frequency addressed optical fiber sensor was the target of an extensive analysis. In particular, a hybrid architecture was studied, which was resulted from the combination of a tree topology with a Michelson topology for the interferometers, which resulted in insensitivity of the lead fibers to the action of spurious influences. A detailed quantitative analysis of the crosstalk levels between the sensors in the network induced by several sources was performed. The results obtained are generically applicable to any multiplexing scheme where the sensors are frequency addressed [4].

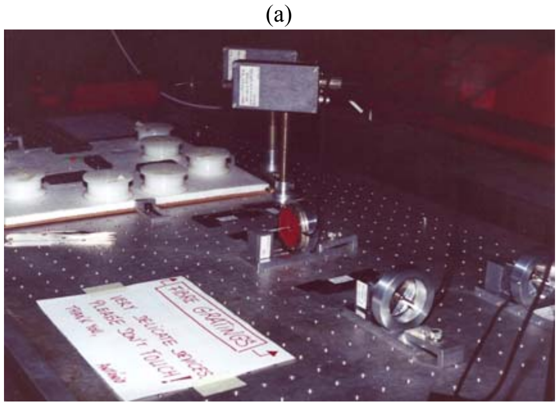
During this research time, coherence addressing of sensors was identified as a promising technique. Hence, a multiplexing architecture in which time addressing of sensors was combined with coherence reading of their signals, and the utilization of multimode laser illumination was studied. The sensors (all fiber Michelson) were distributed in a reflective ladder topology. This configuration allowed the sensors to be physically identical and enabled the possibility of signal demodulation with a considerable non-ambiguous dynamic range, making it possible to recover the system information every time it was turned on (which is particularly important when dealing with quasi-static physical measurands, such as displacement, temperature, pressure, etc.). The possibility of using a multimode laser diode for the optical source was investigated and proved viable with advantage considering the necessity of imposing certain conditions on the values of the interferometer path-imbalances. The outcome was the availability of a low coherence optical source with significant levels of emitted power and high injection efficiency into single mode fiber, with reasonable insensitivity to the effects of coupling to the laser cavity of radiation retro-reflected by the system (thus making unnecessary the utilization of source optical isolators). The source could be directly pulsed via modulation of its injection current by a sequence of pulses necessary to implement time addressing. The experiments performed were complemented by a theoretical study of the system [5].

Multiplexing with birefringent fibers was also studied where the sensors (Mach-Zehnder polarimetric interferometers) were addressed in coherence. Conditions for the relative path-imbalances of the sensors to avoid intrinsic crosstalk were specified, being concluded that it was possible to eliminate this type of crosstalk with values of the path-imbalances that were relatively lumped together. Also, for a multiplexing scheme of this type it was calculated that the spectral density of noise induced by fluctuations of the optical source followed thermal statistics (like superluminescent diodes, important for implementing coherence addressing) [6]. Before the outcome of fiber Bragg gratings, the most promising optical fiber sensing heads were based on Fabry-Pérot cavities. Therefore, these sensing heads were the subject of detailed studies and a new scheme of cavity interrogation based on a time multiplexing technique was proposed and demonstrated [7]. In addition, the implications of the utilization of low-finesse Fabry-Pérot cavity as a sensing element were addressed when its transfer function was approximated to that of a two-beam interferometer. The reading errors that arose from this approach had been quantified for several processing schemers [8].

In the context of a MSc programme, A. B. Lobo Ribeiro built and demonstrated a very high performance, fiber optic system to measure acceleration based upon "white-light" interferometry. Theoretical study of this interferometric technique was conducted with different types of low coherence sources. By using a multimode laser diode (as an alternative to conventional low coherence sources), an all-fiber interferometric system with large tracking range and self-initialization, for remote signal processing of fiber optic accelerometer was investigated. A resolution of better than 1 μg/√Hz and dynamic range of about 90 dB were achieved with this system [9]. A second project concerning the development of an accurate fiber optic pressure sensor (simulator) with "built-in" temperature compensation scheme for borehole gas inspection applications was also demonstrated [10].



(a)



(b)

Fig. 1 (a) Schematic diagram and (b) photo of the first FBG sensing network done at U. Kent.

After this first work focused on low coherence interferometric sensing systems, the PhD research programme was concerned with the possibility of developing some work with a new fiber device which became available at the time: fiber Bragg grating (FBG). A. B. Lobo Ribeiro was responsible for the first FBG sensing and multiplexing experiments performed at the Applied Optics Group of Univ. of Kent. For that initial project, a novel method of in-line FBG sensors was introduced based upon the use of a receiving grating matched to a sensing grating (Fig. 1)[11]. The work originated the first FBG British patent (GB2268581) for the group. The results were very encouraging, and the PhD work continued to progress after that year, with different FBG demodulation schemes [12] and several combinations of optical multiplexing schemes (wavelength division multiplexing + spatial division multiplexing + time division multiplexing) were for the first time demonstrated [13, 14].

3. Fiber optic sensing in Portugal

By the time the authors returned to University of Porto/INESC-Porto, a considerable optoelectronic infrastructure was locally available mainly directed to R&D in optical fiber communications, but with almost direct application for R&D activity in fiber sensing. Hence, the students at the end of their graduate studies became interested in this new area and started their studies on the subject under the supervision of the authors. The dynamism and a set of favourable circumstances induced a fast growth of local research in several fiber sensing topics, in the context of National and European funded projects. The know-how and experience acquired along the years brought the fiber sensing group in Porto to a state that permitted the implementation of technology transfer actions with local companies and, later, the establishment of INESC-Porto spin-off company totally focused on fiber sensing technology (FiberSensing S.A., www.fibersensing.com).

In Portugal during the last 10 years, some activities in fiber sensing had also emerged in University of Aveiro, but it was acceptable to state that the country activity in this R&D area was essentially localized at University of Porto/INESC-Porto. In the following sections, there will be presented with some examples of fiber sensing developments originated in Porto, in most of the cases, in the context of a vast number of collaborations with groups in other countries.

3.1 Intensity sensors

Optical fiber intensity sensors are very attractive since they are conceptually simple, reliable, small in size, and suitable for a wide range of applications at low cost. However, to ensure accurate measurements, the implementation of a reference channel is vital. Such channel should provide insensitivity to source intensity fluctuations and to variable optical transmission losses in the fiber link, couplers and connectors, which are often indistinguishable from transducer. In this context, a self-referencing signal-processing scheme is required in order to have a robust and precise fiber optic intensity sensor. This type of sensors was the first one to be researched at INESC-Porto for many years; their study and application opportunities were addressed benefiting to the progresses of optical fiber technology. Different configurations were analysed, such as: re-circulating loop, Mach-Zehnder, Michelson and Sagnac. As an example, Fig. 2 presents a Michelson topology with optical feedback [15]. The frequency response of such structures, when the input optical power is modulated at a particular frequency, shows that for some frequencies the amplitude of the output optical power waveform is at the maximum (constructive interference frequencies: f_I), while for other frequencies it results in a minimum value for that amplitude (destructive interference frequencies: f_{OI}).

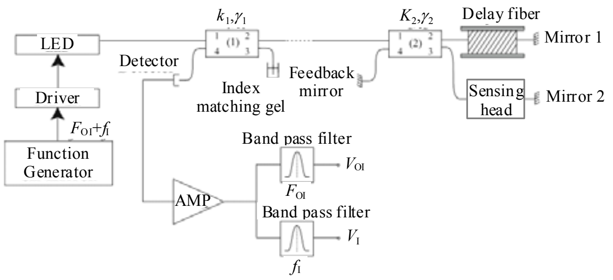


Fig. 2 Block diagram of the intensity based fiber optic sensing configuration using a Michelson topology with optical feedback [15].

Theoretical and experimental transfer functions for the Michelson topology with optical feedback are illustrated in Figs. 3(a), 3(b), and 3(c). The parameter *g* indicates the optical power attenuation factor externally induced in the fiber structure. For g=1, the configuration is power balanced and there is no induced optical loss, while for g=0 all light is lost in the sensing arm. It can be seen that when the induced loss rises, in other words when g gets closer to zero, the difference between peaks and valleys is shortened until the frequency response becomes constant. On the other hand, when no external losses are induced in the fiber interferometer (g=1), the difference between peaks and valleys is at their maximum. The ratio of the value of the transfer function, at an off-constructive interference frequency, to its value at a constructive interference frequency — "R-parameter" — depends only on the optical losses inside the fiber sensing structure (intrinsic and induced losses), and is not influenced by optical power fluctuations that can occur outside the sensing head. Therefore, the modulation of the R-parameter provides a self-referencing scheme that makes the measurand read-out independent of possible unwanted light intensity modulation along the optical system. An experimental result for the R-parameter is shown in Fig. 3(d) [16]. In this case, the sensor includes a microbend optical fiber sensing-head embedded in carbon fiber reinforced plastic (CFRP), which acts as a load cell for structural monitoring in civil engineering. To analyze the self-referencing properties of the sensor, the optical intensity of the source is decreased down to 75 % of its nominal value during the second trial. As can be seen, the system immunity to optical power fluctuations is effective.

As mentioned below, FBGs as sensing elements have been extensively researched in Porto, and the application of these devices for processing has also been considered. An example of this was the development of a referencing concept for intensity sensors based on the use of fiber Bragg gratings [17]. As shown in Fig. 4, the intensity sensor is designed as a reflective cavity for primary displacement measurement. It uses two identical FBGs: one in the sensor head and the other in the processing region.

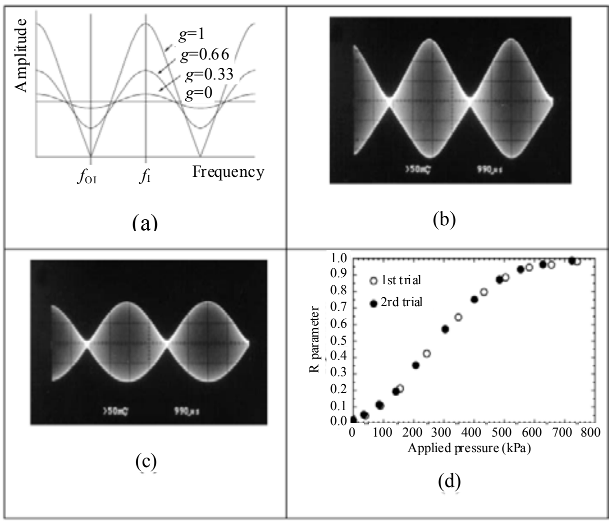


Fig. 3 Transfer function of the Michelson configuration with optical feedback: theoretical result (a), experimental results for (b) g=1 and (c) for g<1, and experimental results for R-parameter versus applied pressure (d) [15, 16].

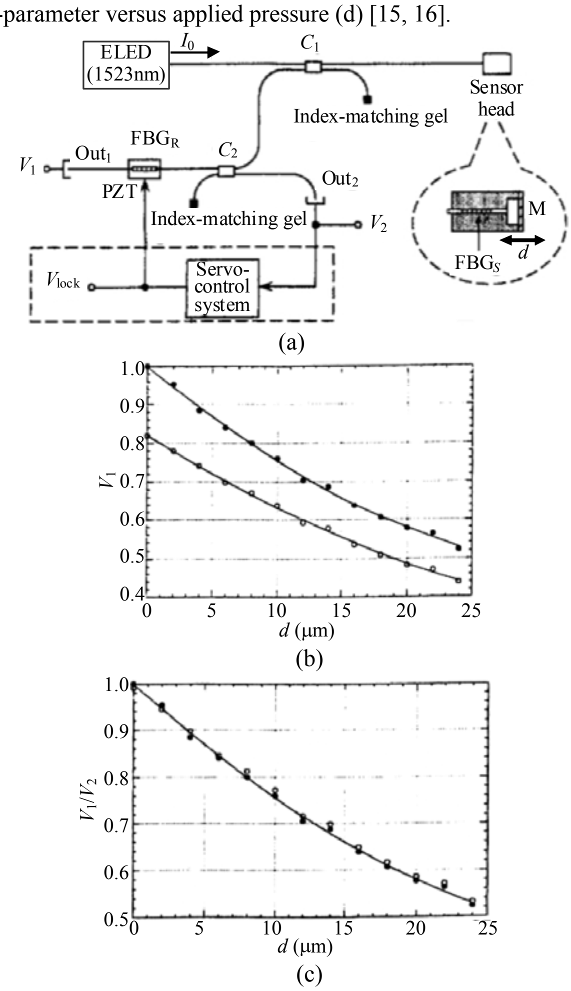


Fig. 4 (a) Experimental setup of the self-referenced fiber optic intensity sensor based on the utilization of fiber Bragg gratings, (b) transfer functions of the sensor without referencing, and (c) transfer functions of the sensor with referencing [17].

The optical power at the Bragg wavelength (BW), is reflected by the grating in the sensing head and provides the referencing signal. All the other input spectral power is transmitted by the grating and is modulated by the measurand. After reflection in the mirror at a distance *d*, a fraction of this power is re-injected in the lead fiber. The discrimination of the sensing and referencing optical powers is performed in wavelength domain by using a second FBG, as indicated in Fig. 3(a) (that is, FBG_R). When this grating FBG_R is pre-strained in such a way that the gratings spectral signatures coincide, the ratio between the signals V_1 and V_2 is independent of the optical power I_0 injected in the input fiber, as well as of any other power fluctuation along the common path of the sensing and referencing signals. Figure 4 also shows the transfer function of the intensity sensor without and with reference signal. This referencing technique is independent of the structure of the sensing head, being the only requirement that must be of reflective type. Additionally, the variations of voltage V_{lock} in Fig. 4(a) are proportional to the temperature variations of the sensing head. The concept of amplitude-phase-conversion for referenced interrogation of intensity sensors have been widely studied and supported by the utilization of FBGs as processing elements (Fig. 5). The optical power into the system is sinusoidal modulated at a particular frequency. Two signals are obtained from the sensing head. The first one comes from the reflection of a FBG located before the transducer that operates at a certain wavelength. Therefore, this signal is not affected by the measurand. The second signal is obtained from another FBG with a slightly different resonance wavelength, located after the transducer and thus containing the measurand information. Considering that there is no optical interference present in the system, since spectral overlap is absent, only electrical beating of these two signals can be expected at detection. The phase of this beating signal is only dependent on the induced measurand loss in the sensing head, being independent of any other losses along the system.

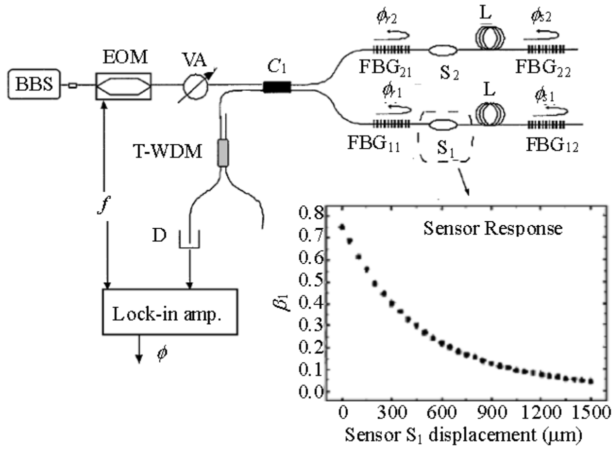


Fig. 5 Experimental setup for interrogation of intensity fiber optic sensors based on amplitude-to-phase conversion [18].

With this technique, the system response has been demonstrated to be almost unaffected by network power variations as high as 90% of the total power launched by the source [18].

In a novel and recent development, the drawback of the interrogation concept shown in Fig. 6, namely the use of fiber delay lines in the sensing head, was overcome by implementing an electronic delay scheme using FBGs as optical processing elements. Figure 6 shows the proposed structure that was proved to work in a highly efficient way [19, 20].

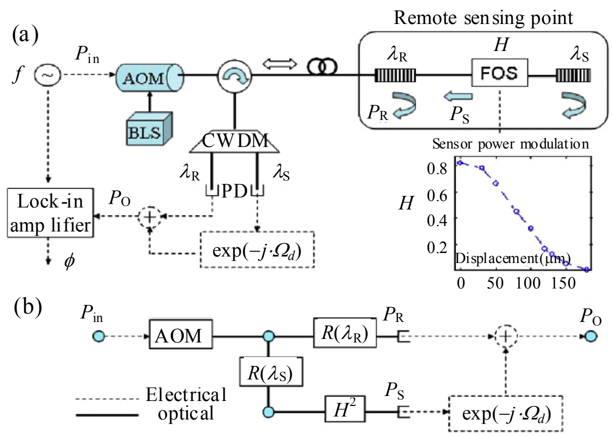


Fig. 6 Experimental setup for interrogation of intensity fiber optic sensors based on amplitude-to-phase conversion without fiber delay lines [19, 20].

3.2 Interferometric sensors

Single mode fiber maintains the coherence properties of the radiation that propagates along the fiber, a feature that opens the possibility of implementing fiber sensors based on phase modulation. Almost all physical measurands introduce modifications to the phase of the propagating light. If the effect is too small to be directly detected, the design of an adequate interface between the fiber and the measurand will increase signal coupling by several orders of magnitude. In the context of optical fiber sensors and not considering fiber Bragg grating based sensors, it is the domain of phase (interferometric) sensors where the largest investments occurred, both in terms of basic research and in terms of prototype design. The main reason for this effort is because of the extremely high sensitivity that these sensors can offer. This high performance level also motivated the research of this type of sensors at University of Porto/ INESC-Porto, particularly in the development of techniques for their interrogation and multiplexing.

The analysis of particular interferometric sensing structures, such as the low-finesse Fabry-Pérot interferometer (LFFPI), has been studied for many years. In many potential applications, the requirement of small sensor heads to perform sensitive point measurements remains the main decision criteria. Before the appearance of fiber Bragg gratings, the LFFPI structure with a short optical cavity was the only attractive choice for the basic sensing element. Such interferometers exploit the cleaved distal end-face of the optical fiber as one interface and an external reflecting surface as the other, or alternatively, the two air-glass interfaces of a length of optical fiber can be used. The LFFPI offers the advantages of being simple and compact, provides high measurand sensitivity, and is lead-insensitive because any environmental fluctuation that affects the optical phase or the light polarization along the optical fiber-lead system is common to the interfering optical fields.

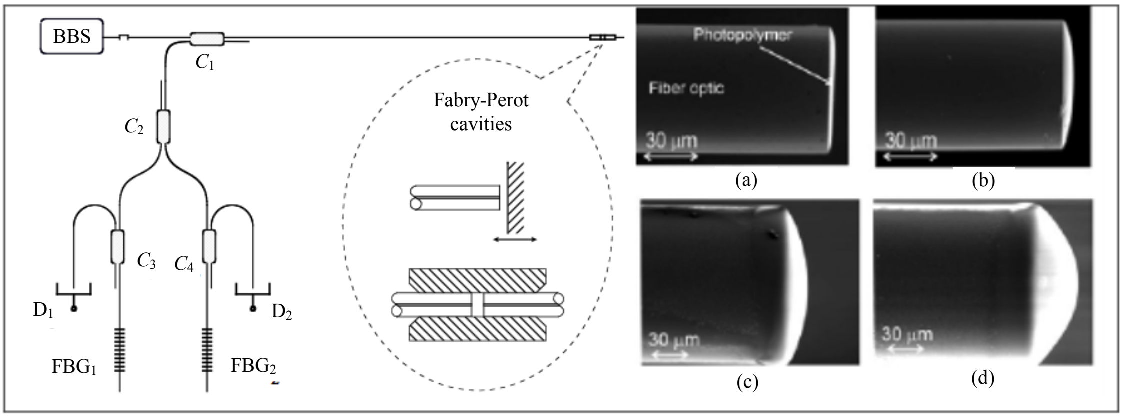


Fig. 7 Experimental setup for FBGs based generation of quadrature phase-shifted signals for interrogation of remote Fabry-Perot interferometers (bottom: scanning electron microscope photos of photopolymer fiber tips fabricated with widths of (a) ≈ 5 μm, (b) ≈ 10 μm, (c) ≈ 22 μm, and (d)≈ 35 μm))[21].

A technique based on the utilization of FBG to interrogate fiber interferometers was developed in the Group and used to interrogate a Fabry-Pérot (FP) interferometer based on photopolymer growth (Fig. 7) [21]. The photopolymer micro-cavity was grown on the tip of a single-mode fiber by the dip-coating technique. Figure 7 also shows scanning electron microscope (SEM) images of photopolymer fiber tips fabricated with different numbers of immersions. For the case of the photopolymer cavity with a width of about 10 μm, a temperature phase sensitivity of about 15 degrees/ ℃ was found. Assuming a modest phase resolution of 1 mrad, corresponds to a temperature resolution of about 67 μ℃, which is illustrative of the sensitivities that can be achieved with these materials and the processing technique used.

Another developed approach to interrogate remote FP interferometers relys on the modulation of the transfer function of a wavelength division multiplexer (WDM). The basic concept is illustrated in Fig. 8. The processing can be based on sawtooth or sinusoidal modulation of the WDM interaction length. For the first modulation format, a FP displacement sensitivity of about 0.2 nm/√Hz was achieved [22].

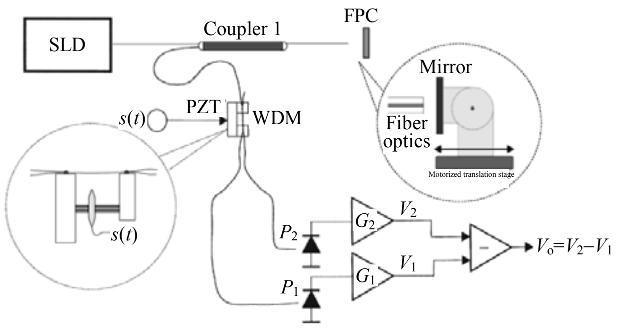


Fig. 8 Interrogation of a Fabry-Pérot interferometer using a tunable WDM [22].

Another type of fiber interferometer that has been studied at INESC-Porto for sensing applications is based on modal interference. Figure 9 shows an example of a structure of this type identified as an LPG(long-period fiber grating)-assisted modal interferometer. Light from a super-luminescent diode (SLD), operating at 1320 nm with a full-width at half-maximum (FWHM) spectral width of about 35 nm (coherence length L_c≈33 μm), is injected into the system. After crossing a 50-50 routing coupler, roughly half of the input power is guided to the LPG-assisted fiber modal Michelson interferometer. The LPG couples a fraction of this light to a specific cladding mode, whereas the remaining light keeps propagating in the fiber core. At the fiber end a silver thin film reflects the light back to the LPG, which induces again cross-coupling between the core and cladding modes. The light that propagates down the core fiber has contributions from the light propagating in the core and cladding modes in the sensing region, which accumulates a differential optical path delay (much larger than L_c) that is dependent on the measurand action [19].

To detect the phase changes in the fiber Michelson modal interferometer, a second interferometer is built to implement coherence reading. It is a conventional fiber Michelson interferometer, with an open-air path in one of its arms, which is adjusted to match the optical path difference of the sensing interferometer. The fiber in the other arm of the receiving interferometer is wrapped around a ring-shaped piezo-electric transducer (PZT), modulated with an electrical sawtooth waveform with certain amplitude to obtain a signal at the photodetection with certain characteristics. After adequate electronic filtering, this signal has the form of an electric carrier (frequency of about 90 Hz), with a phase that mirrors the optical phase of the tandem interferometric system. This pseudo-heterodyne processing technique is known to provide sensitive interferometric phase reading. Figure 9 also shows some results obtained. In the refractive index region around 1.42, it turns out resolution values of 9.0×10^{-5} and 4.6×10^{-5} for the standard and etched fibers, respectively.

Another example of modal interferometry for sensing applications is shown in Fig. 10 [24]. It is a taper-assisted fiber modal interferometer, which is probably the simplest fiber optic interferometric configuration. The effect of the optical taper is to expand the core mode field and to couple light into the cladding modes, which propagates up to the end of the fiber. The fraction of the light that is coupled to the cladding depends on the taper length and depth, and in the present case these parameters are chosen to have a high fringe visibility in the interferometric structure. The fraction of the light

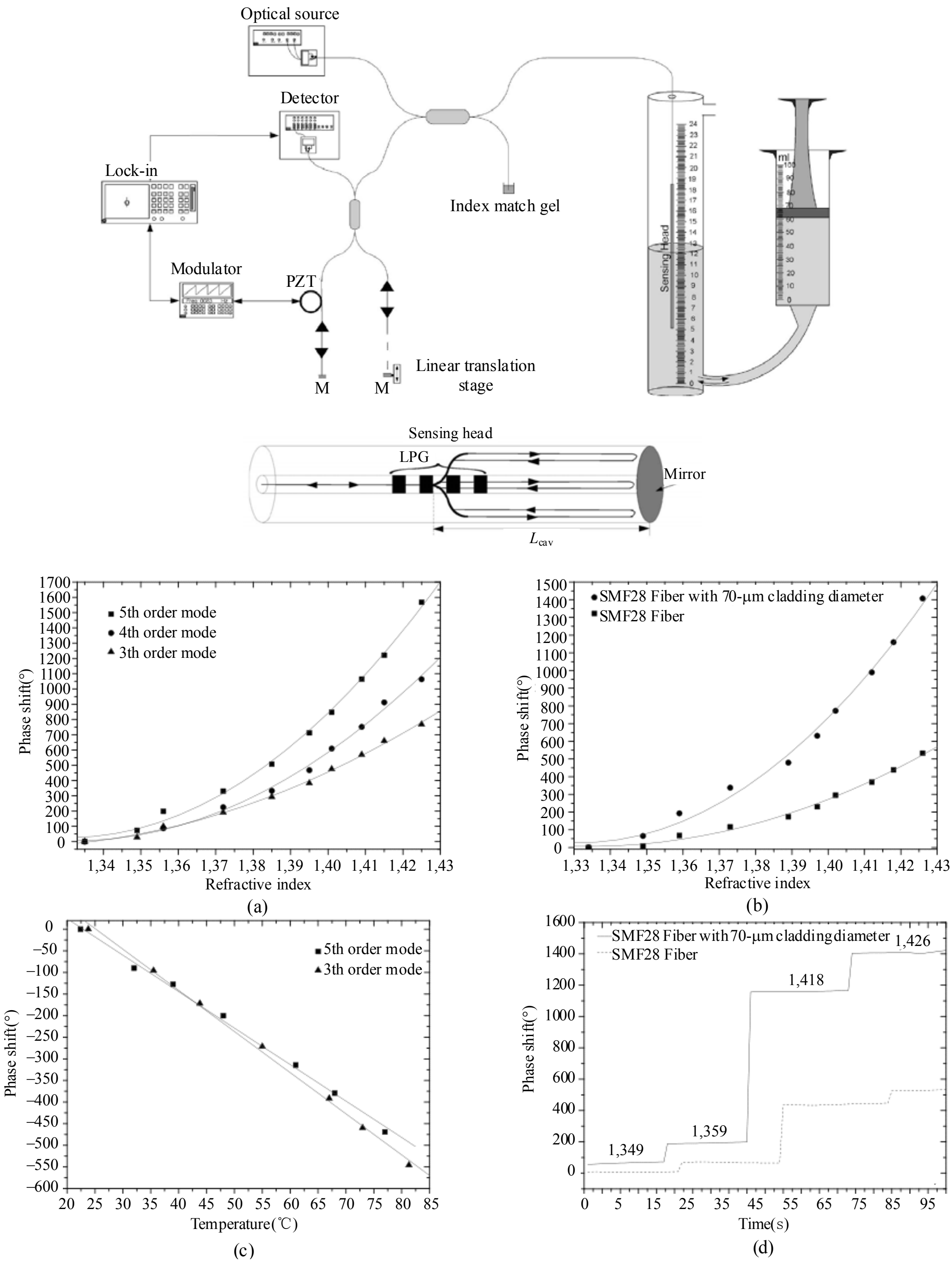


Fig. 9 LPG-assisted fiber modal interferometer and interrogation approach based on coherence addressing and heterodyne processing. Results obtained for refractive index sensing are also shown [23].

that is reflected back goes again through the taper, which induces a recombination effect, originating light waves that propagate down the fiber coming from the core and cladding regions in the sensing length. It is observed that the interferometric phase is highly sensitive to the inclination of the fiber after the taper. Indeed, the own weight of this fiber induces an inclination from the horizontal position that produces a change in the interferometric phase of the order of 150° . Therefore, this structure can be used as highly sensitive curvature sensor. However, in this work we choose to take advantage of this characteristic to build a flowmeter. The concept is illustrated in Fig. 10. With the geometry shown, without flow of air the sensing fiber is under maximum inclination due to its weight. This inclination is reduced when the flow increases, or equivalently, with the increase of the input pressure. Therefore, the interferometric phase will have dependence on this pressure (compressed air in the range of 0.5–3 bar), which is confirmed by the data shown also in Fig. 10, where it is a linear relation between the two parameters (slope of 69.8 degrees/bar, with a maximum error of about 3%).

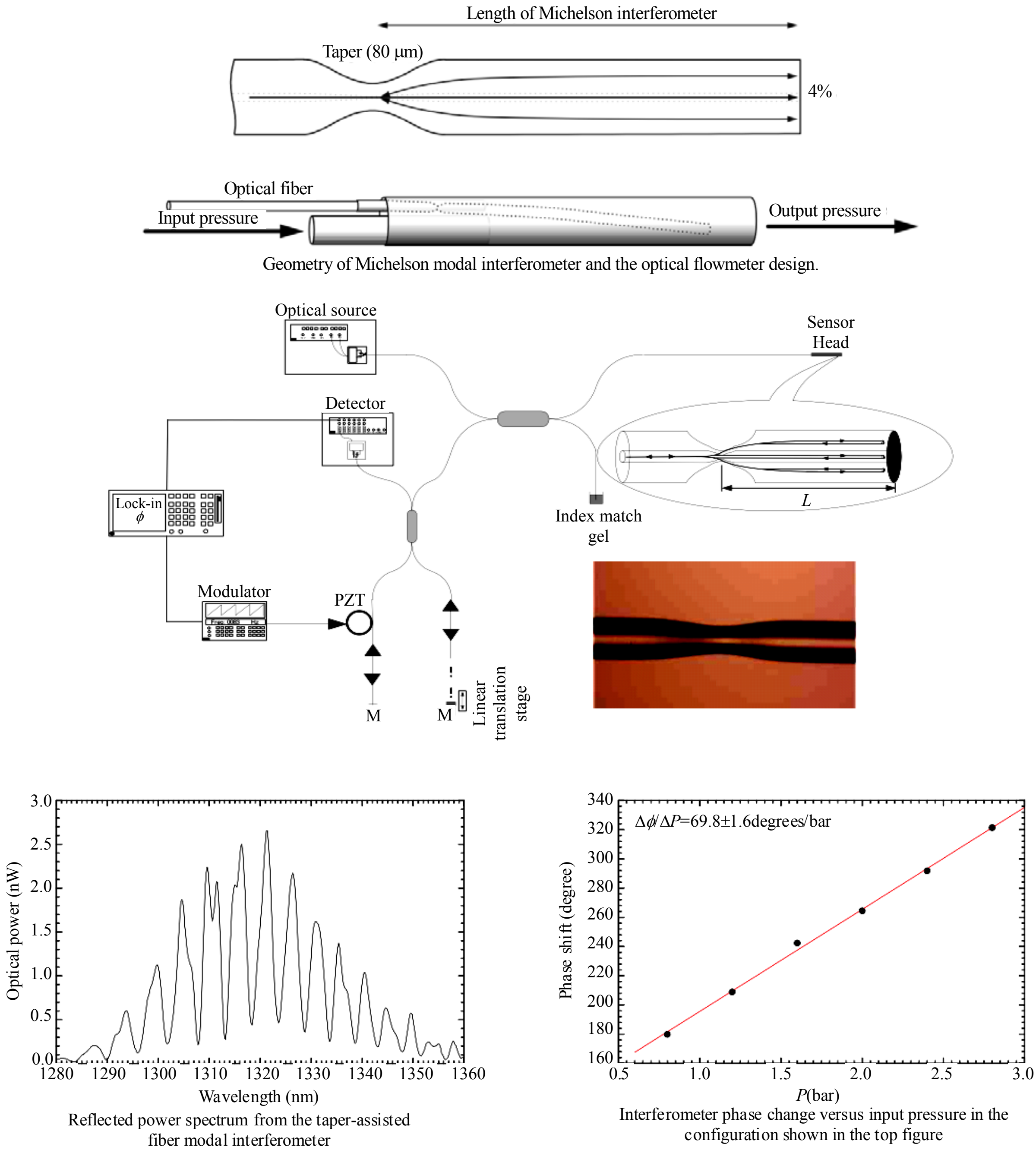


Fig. 10 Fiber modal interferometer based on a fused taper and application as a pressure sensor [24].

3.3 Fiber gratings

Optical FBGs are simple, versatile and small intrinsic sensing elements that can be written in silica fibers, and consequently have all the advantages normally attributed to fiber sensors. In addition, due to the fact that the measurand information is encoded in the resonant wavelength of the structure, which is an absolute parameter, these devices are inherently self-referenced and can be easily multiplexed, which is particularly important in the context of distributed sensing.

A. B. Lobo Ribeiro and others built and fabricated the first FBG fabrication unit in Portugal at INESC-Porto, obtained successfully the first FBG in 1994, an early date in the context of the exploitation of this technology to sensing purposes. Due to that, several collaborations were established with international groups, which outlined a burst of activity around these devices. Topics addressed include: photosensitivity mechanisms responsible for the ultra-violet (UV) induced imprint of the refractive index modulation pattern; FBG interrogation; R&D of sensing heads based on FBG; application of these devices as optical signal processing elements. The know-how acquired along the years permitted the ideal conditions to launch the INESC-Porto spin-off company, FiberSensing S. A (www.fibersensing.com).

A LPG couples light from a guided mode into forward propagating cladding modes where it is lost due to absorption and scattering. The coupling from the guided mode to cladding modes is wavelength dependent, so we can obtain a spectrally selective loss. It is an optical fiber structure with the properties periodically varying along the fiber, such that the conditions for the interaction of several co-propagating modes are satisfied. The period of such a structure is of the order of a fraction of a millimeter. In contrast to the FBGs, LPGs couple copropagating modes with close propagation constants; therefore, the period of such a grating can considerably exceed the wavelength of radiation propagating in the fiber. Because the period of an LPG is much larger than the wavelength, LPGs are relatively simple to manufacture. Since LPGs couple co-propagating modes, their resonances can only be observed in transmission spectrum. The transmission spectrum has dips at the wavelengths corresponding to resonances with various cladding modes (in a single-mode fiber). University of Porto/INESC-Porto has extensively studied the characteristics of these devices, particularly those fabricated using the techniques based on electric arc-discharge and mechanical action. Their properties were fully characterized, essentially aiming their application as sensing elements.

3.3.1 Fiber Bragg gratings

Figure 11 shows the experimental setup implemented to test the FBG interrogation concept based on the modulation of a multimode laser diode. It relies on the generation of an electric carrier by using a modulated multimode laser diode to illuminate the FBG. The change in Bragg wavelength is measured by tracking the phase of the carrier at the detector output, in an open or closed-loop configuration. A pigtailed multimode laser diode operating at 1318 nm (wavelength of the central mode) was used to illuminate the FBG in the spectral position of one of the laser lateral modes. By modulating the injection current, the laser wavelength was modulated by a sawtooth signal at 1 kHz. Figure 11 also shows the output signal as seen on the scope. Since the laser line spectral width is much smaller than the grating spectral width, sweeping the grating spectrum with the laser mode reveals the spectral structure of the fiber grating. The demodulation principle is also illustrated in the same figure, which displays the change in the output signal when the system is operated in open loop and the strain applied to the grating changes by $\delta\varepsilon = 233$ με [25].

The closed loop format is set when the switch in

Fig. 11 is closed, in which case the change in Bragg wavelength is measured by monitoring the laser bias current. In this mode of operation, the system response to applied strain and temperature is given in the bottom of Fig. 11. From the data spread and the bandwidth of the feedback loop (~ 20 Hz), resolution of 0.05 ℃ /√Hz and 0.7 με/√Hz are achieved.

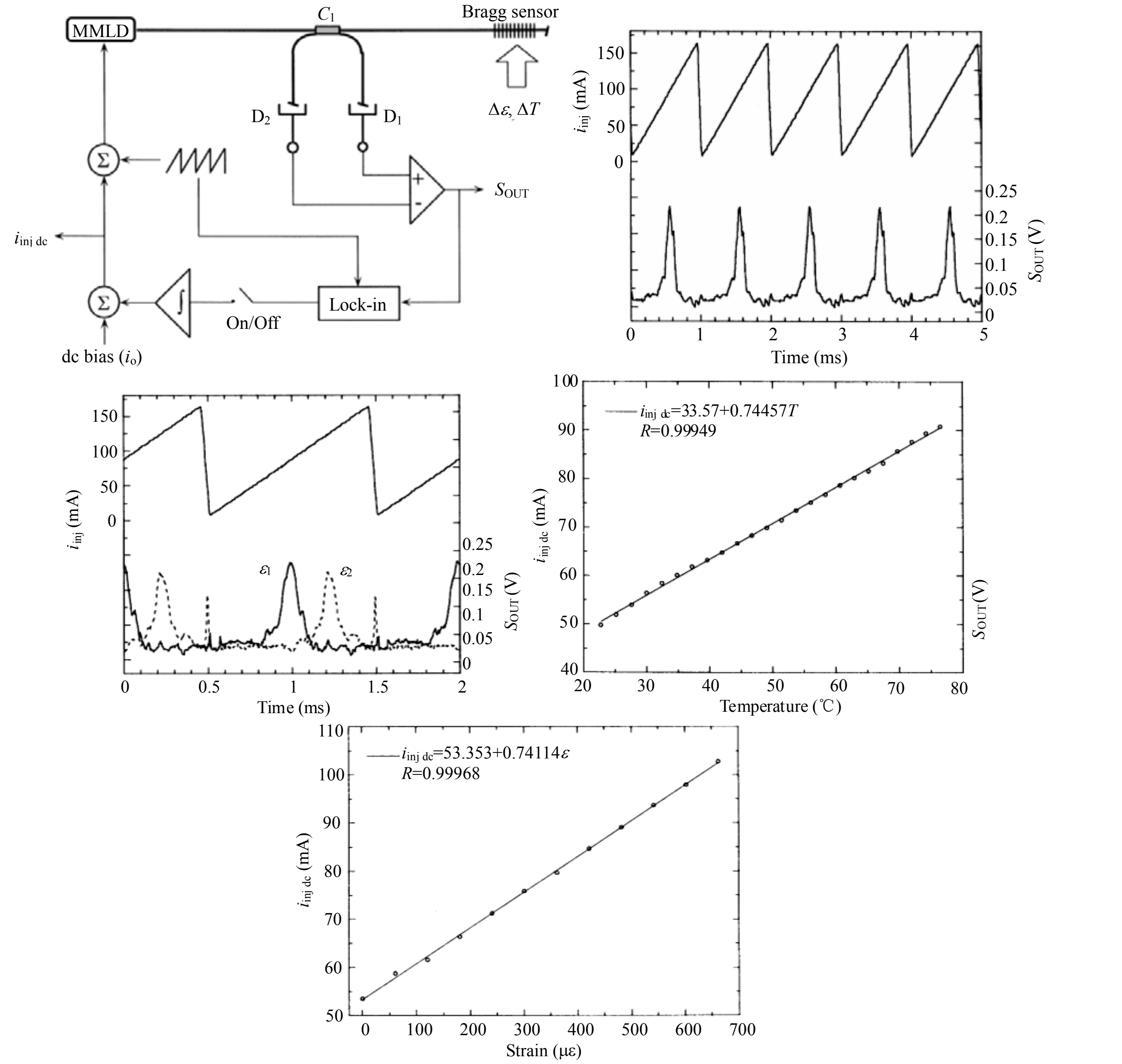


Fig. 11 Experimental setup for FBG interrogation based on the sawtooth modulation of a multimode laser diode (top); sawtooth waveform applied to the laser diode and corresponding output carrier (middle left); demonstration of the effect on the output carrier when the strain applied to the sensor head changes by ε_2–ε_1 = 233 με (middle right); system response to temperature and strain changes [25].

Figure 12 shows a miniaturized sensor configuration based on fiber Bragg gratings for simultaneous measurement of curvature, plane of curvature and temperature [26]. Due to the particular geometry of the sensing head, it is possible to not only measure the curvature radius, but also determine the plane of curvature. This is achieved by arranging three Bragg gratings in the vertices of the smallest equilateral triangle that can be defined by the cross sections of the fibers. The set is then inserted in a glue-filled capillary stainless-steel tube to provide both a suitable protection for the Bragg sensors and rotational symmetry to the sensing head. This tube also ensures isolation from axial-strain, allowing the additional determination of temperature. The proposed sensing head is particularly well suited for applications in smart structures because it can be embedded along any layer of a composite material (including the neutral line) without special concerns on the relative orientation of the Bragg gratings arrangement and the composite layers. This sensing configuration may also be used to implement more sophisticated sensors dedicated, for example, to the measurement of multi-axial acceleration or flow and temperature.

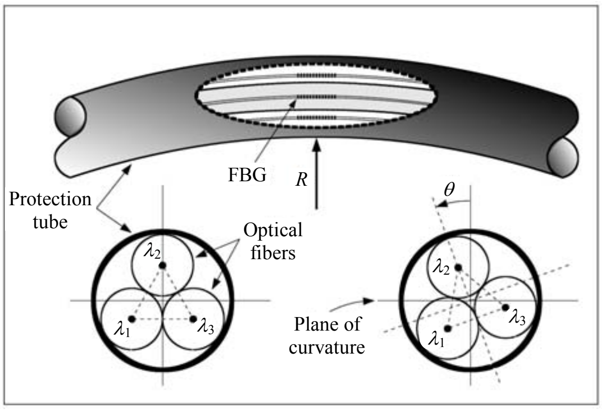


Fig. 12 Geometry of the sensing head based on FBGs to measure curvature, plan of curvature and temperature [26].

The simultaneous measurement of several parameters is an important topic, not only because, in general, it allows minimization of the complexity, size and cost of a measurement system, but also as it fulfils the need to perform parameter discrimination in situations where cross-sensitivity is a crucial issue. As an example of this situation, the measurement of slowly varying strain is an important application of optical fiber sensors, but such measurement can be severely corrupted by the temperature cross-sensitivity, a situation that implies the need to independently measure these two parameters. The simplest way of measuring strain and temperature is to use physically separate sensing elements, where the first one is isolated from strain and experiences only temperature changes, and the second one is actuated by both strain and temperature. Provided that two sensing elements are at the same temperature, the output from the first sensor can be used to derive a temperature-corrected strain value from the second sensor. Various dual sensing element arrangements have been used, including serial deployment of in-fiber Bragg gratings, or various forms of common-mode rejection. However, where sensors must be embedded with minimum intrusion in the measurement volume, the use of a second sensing element is not feasible. In these situations, strain and temperature measurement (or sets of other measurands) must be performed by a single sensing element. This issue has been the focus of intensive research worldwide and in the Group.

Figure 13 illustrates one concept for simultaneous measurement of temperature and strain, which is based on the combination of two Bragg gratings, written in different single-mode fibers (such as SMF-28 type, 3 mol% of GeO_2; FiberCore PS-1500 type, 10 mol% of GeO_2, 14 mol%–18 mol% of B_2O_3) and with different reflectivities, to form a single signature with a stepped reflection spectral profile. The peak wavelength shift ($\Delta\lambda_{peak}$) and the spectral width at 6 dB (SW_{6dB}) of the stepped FBG structure were measured for different values of temperature and applied strain. The former ($\Delta\lambda_{peak}$) corresponds to the response of the B/Ge-doped fiber, while the latter (SW_{6dB}) corresponds to the combined response of both types of fibers under applied strain and/or temperature. Linear dependences of these parameters with temperature and strain are observed with slopes that permit a system of two independent equations for ΔT and $\Delta\varepsilon$, from which it is possible to calculate these values through measurements of $\Delta\lambda_{peak}$ and SW_{6dB}. The achieved resolutions can be obtained from the diagram shown in Fig. 13, turning out to be 0.7 ℃/$\sqrt{\text{Hz}}$ and ± 2.6 με/$\sqrt{\text{Hz}}$ [27].

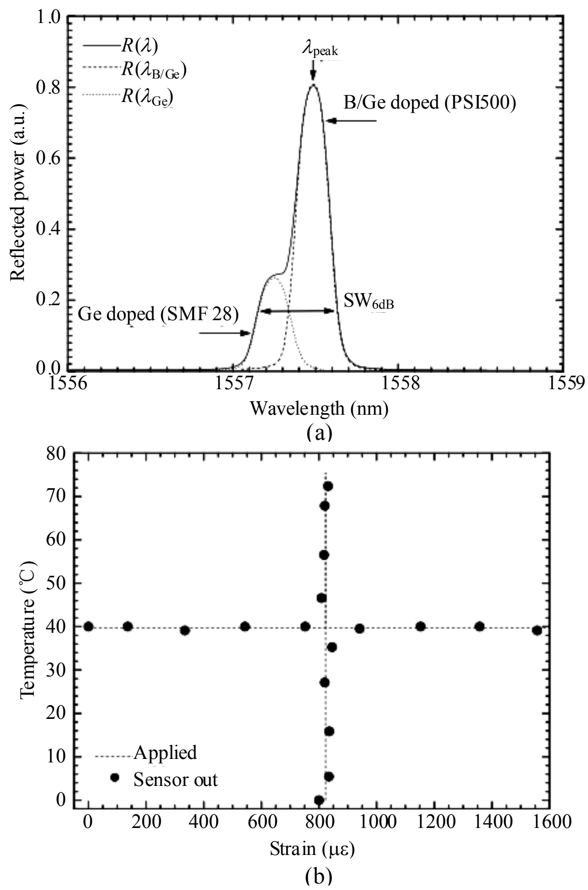


Fig. 13 (a) Stepped spectral profile as reflected by FBG arrangement and (b) sensor output as determined by the matrix equation for applied strain at constant temperature [27].

3.3.2 Long period gratings

It is well known that LPGs are sensitive to variations of the refractive index of external medium. Several factors associated with this property were studied in the Group, in particular the sensitivity enhancement of LPGs written in pure-silica-core fibers relatively to those written in standard fibers. The main result is given in Fig. 14 where the spectral shift of the resonance of these two types of LPG in air and immersed in water is shown. From this it can be concluded that the LPGs in pure-silica core fibers show about 3 times increase of the sensitivity when being compared to gratings written in standard fibers [28].

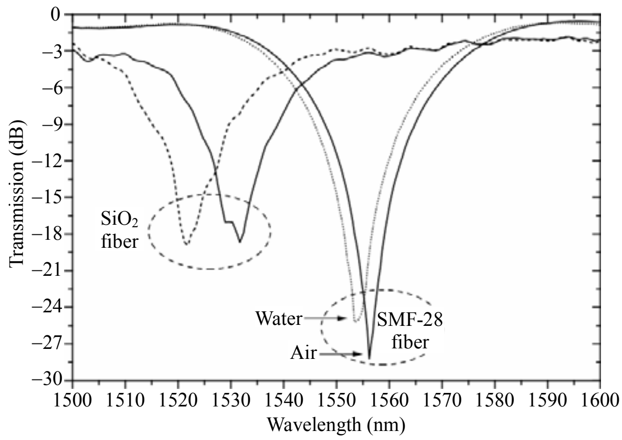


Fig. 14 LPGs spectra in air and in water for two different fibers [28].

3.4 Sensor in photonics crystal fibers

Since the first publication by Knight *et al.* in 1996 on photonic crystal fibers (PCF), the optical fiber community has been continuously engaged on R&D activities around these new fibers. Indeed, the fiber structure with lattice of air holes running along its length shows remarkable properties that support a large variety of novel optical fiber devices which can be used both in communications and in sensing systems. A commonly accepted classification of PCF divides them into two main classes: index-guiding PCF and photonic band-gap PCF. For both types of PCF fibers, the big attraction is that by varying the size and location of the cladding holes and/or the core diameter, the fiber transmission spectrum, mode shape, nonlinearity, dispersion and birefringence can be tuned to reach values that are not achievable with conventional fibers. For sensing, as well as for communications, this characteristic brings the possibility of designing sensing heads with qualitatively new performances, which constitutes a breakthrough in the optical fiber sensing technology.

Benefiting from collaborations with European R&D Groups that have facilities for PCF fabrication, recently University of Porto/INESC-Porto has been working extensively on the R&D of PCF based platforms for sensing [29]. Bragg gratings written in

PCF fibers show sensing properties different from those present in standard fibers. This was explored to perform simultaneous measurement of strain and temperature. In one of the configurations researched [30], the sensing head consisted in a standard SMF 28 fiber length spliced to a length of microsctrutured fiber (Hi-Bi). FBGs distanced by 10 mm apart were written in both fibers using the phase mask technique described above. The same phase mask was used in both cases, resulting in Bragg wavelengths of 1556 nm for the SMF and 1508 nm for the micro-structured fiber (MOF) (λ_{fast}). This difference is translated into a difference of the fiber modes effective refractive indexes Δn_{eff} of about 4.26×10^{-2}. Figure 15 shows the cross section of the PCF fiber. The spectral signature of the FBG structure in the PCF is shown in Fig. 16(a). It was observed that the strain sensitivity and temperature sensitivity were substantially different for these gratings, particularly the temperature, where the difference between the sensitivity coefficients reached about 60%. The large volume of the holes, which are filled with air, has a determinant effect on the thermo-optic coefficient of the MOF, decreasing the temperature sensitivity of the FBGs written in this type of fibers. On the other hand, the strain coefficient of the sensing head MOF grating is about 9.6% larger than the one relative to the SMF grating. This result is a consequence of the reduction of the Young modulus in the MOF due to the presence of holes.

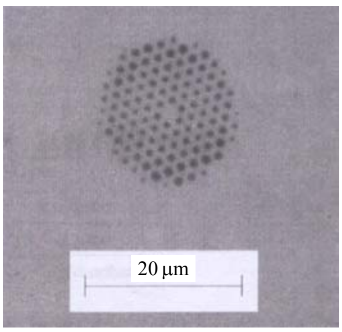


Fig. 15 SEM image of the cross section of the microstructured optical fiber (NL 2.3 1555).

In view of the different strain and temperature sensitivity of two gratings, it is feasible to measure simultaneously temperature and strain. The results shown in Fig. 16(b) were obtained, from which we obtained resolutions of ± 1.5 ℃ and ± 10.7 με for these two measurands.

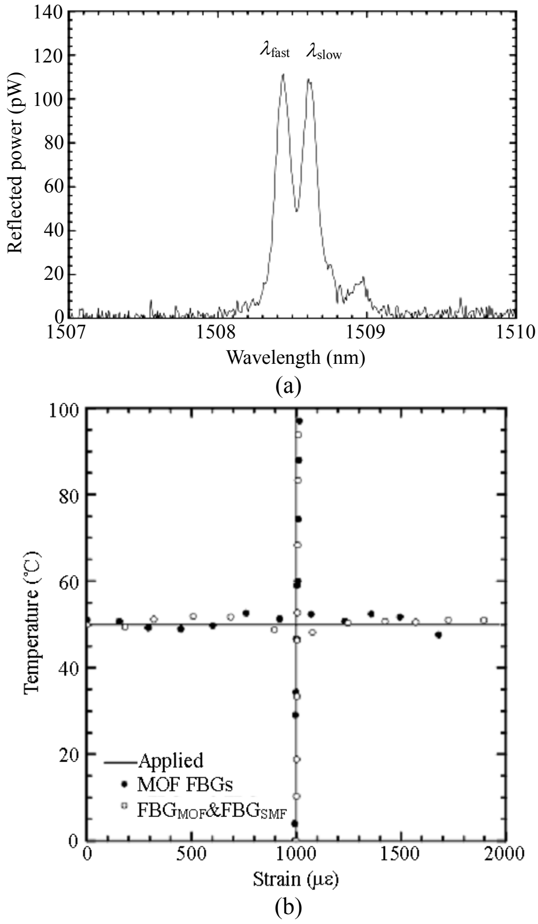


Fig. 16 (a) Optical spectrum of FBG written in PCF and (b) determination of sensor resolutions [30].

In another work, a new FBG refractometer based on an H-shape fiber was demonstrated (Fig. 17) [31]. H-shape fiber was formed when a Hi-Bi side-hole fiber undertook chemical etching (side-hole fiber fabricated in Wroclaw University of Technology). The two holes of the side-hole fiber were open, allowing the evanescent field of Hi-Bi FBG to interact with the external liquid. Due to the birefringence of this sensing structure, it was indeed possible to measure simultaneously refractive index and temperature. The results obtained indicated resolutions of about 0.01 RIU and about 1.6 ℃ for liquid refractive index and temperature, respectively.

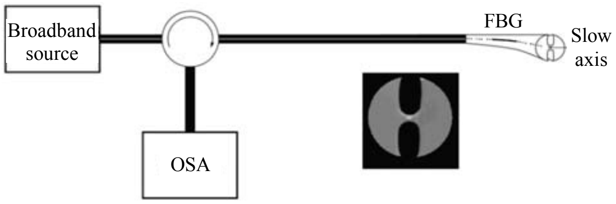


Fig. 17 Experimental setup of the FBG refractometer based on H-shape fiber [31].

Suspended-core fibers are also considered for sensing applications. Figure 18 shows a fiber optic Fabry-Perot sensing structure based on the utilization of a suspended-core fiber. The interferometric structure is formed when a small length of suspended-core fiber (fabricated at Institute of Photonics Technology (IPHT) of Jena, Germany) is spliced to the end of a standard single mode fiber. The interfering waves are generated by the refractive-index mismatches of the two fibers in the splice region and the suspended-core fiber-end [32].

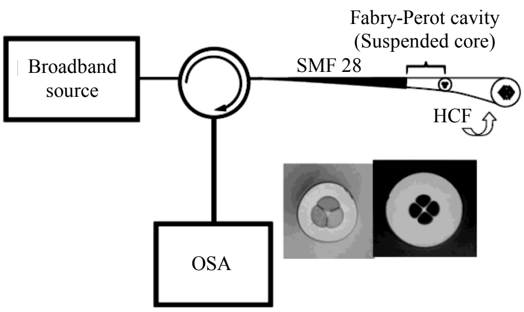


Fig. 18 Experimental setup with the sensing head (right: photos of the suspended-core fiber with three and four holes are shown) [32].

Thermal and strain responses of two different sensing heads associated with suspended-core fibers with three and four holes are characterized, and the results obtained are summarized in Table 1.

Table 1 Strain and temperature sensitivity coefficients obtained with these fibers [32].

Fabry-Perot	Strain sensitivity (pm/με)	Temperature sensitivity (pm/K)
Three holes	1.32	7.65
Four holes	1.16	8.89

3.5 Electric current sensors

The measurement of certain parameters in specific environments has been of major importance in the development of fiber optic sensing technology. The fiber hydrophone for detection of objects in deep sea (based on Mach-Zehnder interferometers), the fiber gyroscope (relying on the Sagnac interferometer), and the electric current fiber meter (based on the magneto-optic effect) are at the top of this list. Focusing on the measurement of electric current intensity in high voltage environment, optical fiber based solutions experienced considerable development over the last twenty years. Due to the intrinsic dielectric characteristics of the optical sensors, the need for insulation is greatly reduced. On the other hand, the magneto-optic effect, in which most configurations are based, has a constant linear response over a wide range of frequencies and unlike effects employed in conventional sensors, presents no hysteresis or saturation effects in practical magnetic fields. Fiber or bulk closed loop configurations, illuminated by optical fiber guided radiation, are especially attractive because their closed optical path ensures immunity to external magnetic fields, which permits univocal current measurement.

This potential also triggered the R&D of this type of sensor at University of Porto/INESC-Porto. A hybrid configuration, in which the secondary coil of a current transformer was adequately connected to a piezoelectric transducer with a FBG attached to it, resulting in a sensing head with Bragg wavelength shift proportional to the electric current, was developed and successfully tested in real conditions. In another development, another electric current concept based on a metal-coated FBG coupled to a standard current transformer was demonstrated [33]. This structure (Fig. 19) used the temperature induced Bragg wavelength change that occured when the electric current flowed through a thin conductive coating on the surface of a short length of fiber where the FBG was located. In a measurement range up to 400 A (root-mean-square value, or RMS value, in the primary coil of the transformer), a resolution of ± 2 mA was reported.

Due to the limited bandwidth of the sensor (≈ 2 Hz), its response was proportional to the RMS value of the square of the current intensity. However, it was indicated that the frequency response could be increased up to tens of kilohertz by using a sputtering technique to produce a thinner and uniform layer of metal over the FBG.

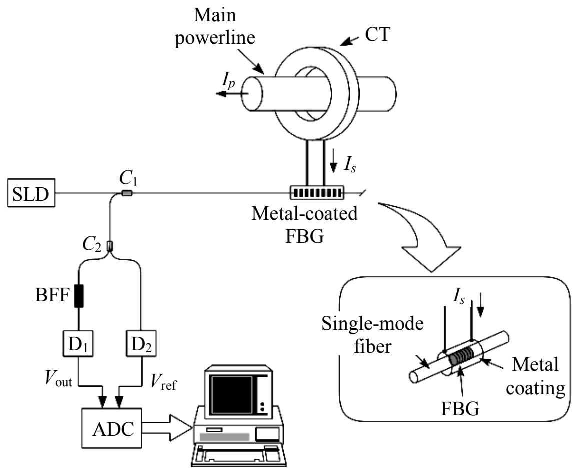


Fig. 19 Metal-coated fiber Bragg grating sensor for electric current metering [33].

A different approach for current metering based on a bulk interferometric configuration was also proposed and demonstrated. The measurand information appears as a phase modulation of a frequency carrier; in this way, the sensor transfer function is independent of optical power fluctuations and has true linear dependence on the current intensity. The sensing head, represented in Fig. 20, is a Mach-Zehnder interferometer with an additional reciprocal loop [34].

The square shaped loop, which works as a Sagnac interferometer, is built with low linear birefringence SF57 glass prisms. In order for the beam remain confined within this loop, internal reflections are needed at the corners. To avoid unwanted phase terms the technique of double reflections with complementary effects in each corner is used. Due to the circular birefringence induced in the square loop by the magnetic field resulting from the electric current to be measured, an optical phase difference is introduced between two orthogonal circular modes propagating in the Sagnac loop. Modulating the injection current of the laser diode with a sawtooth waveform of precise amplitude, a pseudo-heterodyne carrier is generated in the first interferometer (Mach-Zehnder), with its phase modulated by the electric current that propagates through the second interferometer (Sagnac).

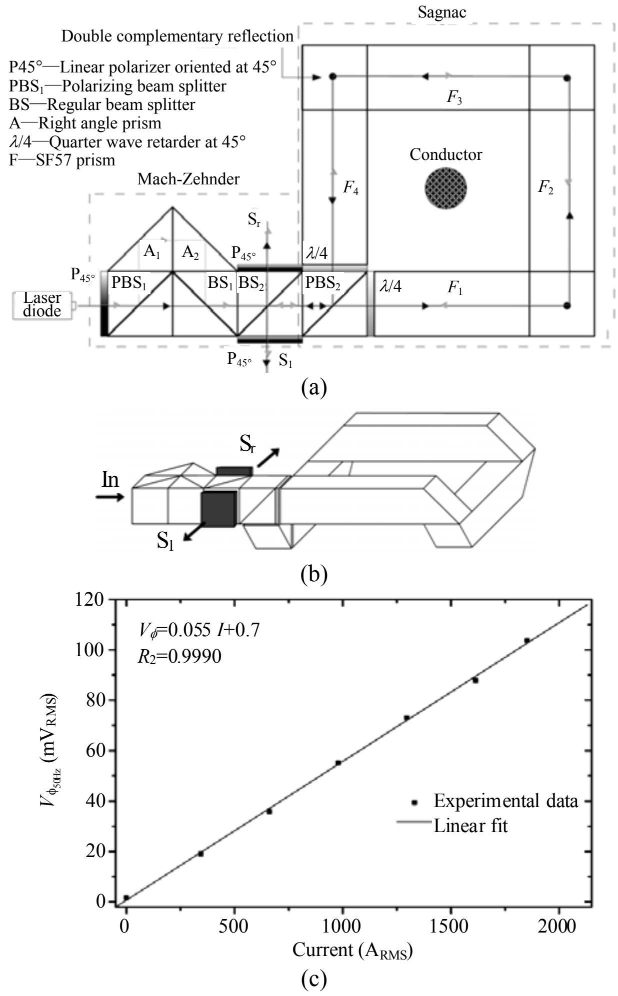


Fig. 20 (a) Interferometric sensing head for electric current metering, (b) 3D view, and (c) system response to applied current [34].

Figure 20(c) shows the system's response to applied current. Its sensitivity was calculated to be 1°•kA^{-1} (RMS), and the measured value was 1.7°•kA^{-1} (RMS). The resolution of current measurement was 17 A_{RMS} /√Hz, a value essentially determined by laser diode induced noise.

3.6 Sensor multiplexing

In applications where sensing arrays are needed, multiplexing of fiber sensors will result in significant cost savings due to the reduction in the number of light sources required, detectors, and fiber transmission lines. A number of different approaches to sensor multiplexing have been reported, which may be described as forms of coherence, frequency, wavelength and time division multiplexing.

In general, multiplexing involves the concepts of network topology, sensor addressing, and sensor interrogation. These concepts are frequently not independent, which means that the choice of one implies the selection of the other two. There are other relevant features conditioning the feasible configurations in a specific application. As an example, the integration of interferometric and intensity-based sensors makes it difficult to utilize reflective networks, since intensity sensors are normally implemented in multimode fiber, which implies the need for the return fiber bus to be also multimode. This constraint demands the utilization of a transmissive type network.

We have also been involved in this specific topic. Several networks and addressing-sensor interrogation approaches were tested over several years. One of them was the utilization of wavelength selective couplers in the research of transparent networks for hybrid wavelength multiplexing of fiber Bragg grating and intensity based fiber sensors, and more recently we demonstrated FBG-assisted wavelength multiplexing of self-referenced intensity sensors (Fig. 21) [35].

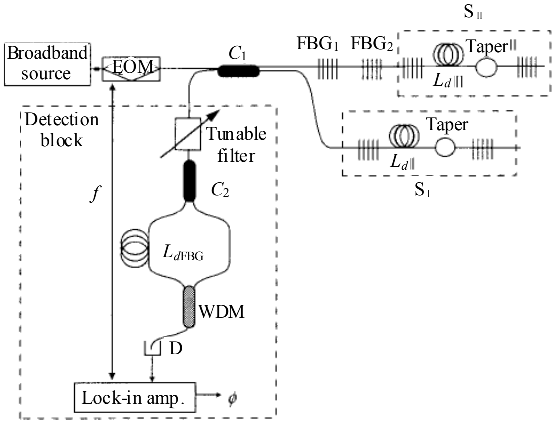


Fig. 21 Multiplexing of fiber Bragg grating based sensors [35].

Here we give an example of a study addressing a topology with interesting characteristics for a fiber sensing transmissive network [36]. It is referred as the progressive ladder topology (PLT), which is illustrated in Fig. 22(a). For the purpose of comparison, Fig. 22(b) depicts the well-known transmissive ladder topology (TLT), which is probably the one that has been often utilized in transmissive networks supporting interferometric and intensity sensors. For simplicity, it is assumed that the transmissivity of each sensor is unitary, and that there are N sensors in the ladder placed in the rungs that are numbered from 1 to N. The fractional power transferred between two fibers in coupler i is k_i, and $(1–k_i)$ is the power that passes straight through. The crucial criterion for system design is to ensure that each sensor returns the same average optical power (I_S) from each rung of the array to the detector, i.e., $I_S(i) = I_S(i+1)$ for all i between 1 and $N–1$. To fulfil this criterion for the PLT network, and considering a lossless system, it is shown that the coupling ratios of all couplers must be identical, with the exception of the first and last couplers, which occupy an asymmetric position in the network. This property is highly desirable because it avoids coupler tailoring along the network, which has implications in terms of system cost and, most important, facilitates the maintenance and repair procedures.

In a real system, it is necessary to consider the losses on the fibers, splices, couplers and so on, which can be lumped together in the couplers, giving a total power attenuation factor of $(1–\beta)$ and $(1–\gamma)$ each time the light crosses a coupler in the input and output buses, respectively. Figure 22(c) shows the results for the coupler power ratios (k_i) as a function of their locations in the ladder, considering a network with 10 sensors, illuminated with 1,300-nm radiation, and total power attenuation factors of $\beta = 0.84$ and $\gamma = 0.93$ (which means lumped losses of 0.75 dB and 0.3 dB, respectively). Not considering the special case of k_{in} and k_{out}, for the PLT system it can be observed from Fig. 22(c) that the spread of values is relatively small, in strong contrast with the TLT case. Therefore, the PLT is an intrinsically balanced configuration, which is a highly desirable characteristic due to the reasons already mentioned. Figure 22(d) shows the behaviour of the PLT and TLT configurations from the viewpoint of the sensor-returned average optical power as a function of the number of sensors. From these results, it turns out that the PLT configuration is also favourable in terms of power budget, with the corresponding positive implications according to sensor sensitivity.

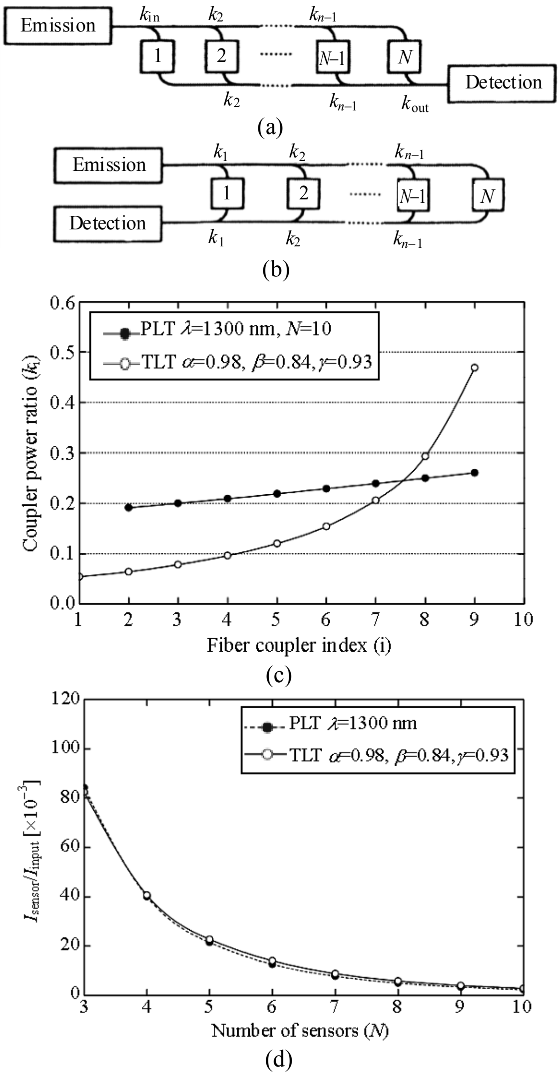


Fig. 22 Fiber optic sensor network topologies: (a) progressive ladder, (b) transmissive ladder, (c) power ratio of the couplers as a function of their locations in the array for the PLT and TLT topologies (N=10, for a real system operating at 1,300 nm), and (d) averaged returned optical power per sensor (normalized by the input power) [36].

3.7 Applications and field trials

After an initial phase of R&D in fiber sensing, as summarized in previous sections, the results obtained by INESC-Porto triggered a certain number of initiatives involving Portuguese companies towards the use of this technology in specific applications. The first of these initiatives occurred in 1997, and involved real time monitoring of the temperature of electric power cables using FBGs, to support an optimization of electric power distribution networks. The problem of conventional technology in the context of electric current metering and current transients in high voltage environments was also addressed. Two optical fiber based configurations were developed that underwent field tests with appreciable performance (Fig. 23).

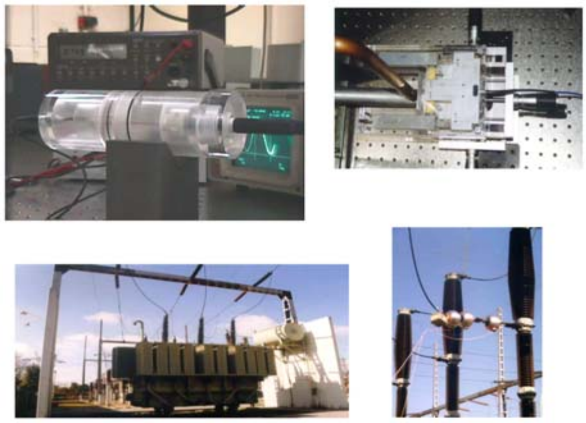


Fig. 23 Optical fiber based sensing heads for current metering in high voltage environments (top) and field tests (bottom) [37].

Another initiative where fiber optic sensors were taken into the field was in the context of environmental monitoring. A project was set aiming to study the dynamics of Ria de Aveiro, an important Portuguese coastal lagoon. One of the required parameters to be monitored was the distribution of water temperature along the 12-km extension of the lagoon, from the connection to the sea up to the location where fresh water was delivered to the system from the feeding river. An optical cable incorporating fiber Bragg gratings was developed and installed. The interrogation equipment, installed in the location, was acquiring data from the FBGs continuously, delivering it to the remote sites of the institutions involved in the project for further processing and analysis. Figure 24 shows one example of the stream of data relative to water temperature measured by three FBGs of the cable.

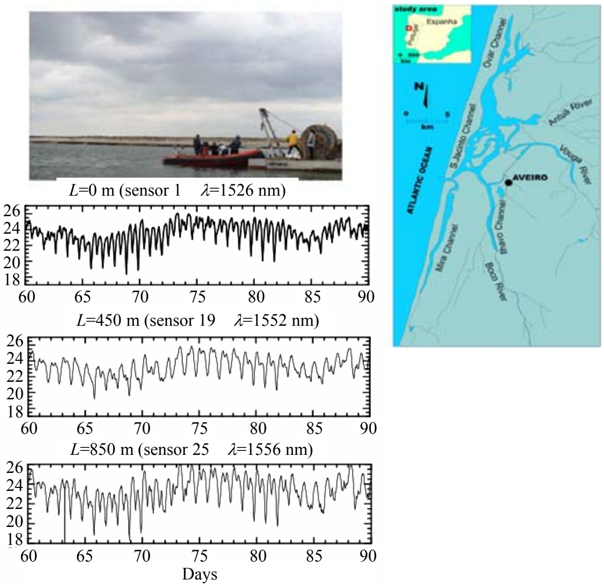


Fig. 24 Installation and localization of the optical fiber sensing cable at Ria de Aveiro (top), and daily variation of water temperature registered along a period of one month by some of the FBGs sensors (L = 850 m is closer to the sea) [37].

Another area where optical fiber sensors, particularly those based on fiber Bragg gratings, offer a high potential as replacement technology is in structure monitoring, mainly in civil engineering. Indeed, Bragg gratings can directly replace electric strain gauges surpassing the limitations of these devices, as their calibration is absolute (optical wavelength), and they are completely immune to electromagnetic interference (EMI) and radio frequency interference (RFI), and, are intrinsically amenable to multiplexing. Consequently, several projects were implemented in the context of civil engineering, with particular focus on the monitoring of concrete bridges and also, historic iron bridges in the city of Porto. The outcome of such actions was illustrative of the advantages of the fiber optic sensing technology relative to the conventional electric based monitoring solutions, and this stimulated the recent launch of a fiber sensing spin-off devoted to the development of fiber optic based sensing systems (www.fibersensing.com). This technology was also tested with success in the context of composite material monitoring for smart structures.

4. Conclusions

Approximately 20 years have gone since the authors started their first “adventures” in the fiber optic sensing field in the notable catalytic environment of the Applied Optics Group of University of Kent, where Prof. David Jackson and his co-workers at the time established what probably was the best school in this field. From Kent, young researchers spread around the globe and locally developed activity in fiber sensing, substantially contributing to a strong position of this sensing area nowadays. In Porto we tried to do the best we could and, probably, it is fair to state that interesting developments come out from this labour, supported by generations of enthusiastic beginners that soon make remarkable high quality R&D and, later, expanded their attention to the economic exploitation of this fascinating technology. So, to all of them the authors would like to express their gratitude for making possible what has been achieved up to now, and certainly much more will come in the future. The final words go certainly to David Jackson, and they are: thanks Professor for providing us the opportunity to be at Kent in the late 1980s and early 1990s.

References

[1] J. L. Santos, T. Newson, and D. A. Jackson, “Electronic speckle pattern interferometry using

single mode fiber and active fringe stabilization," *Optics Letters*, vol. 15, no. 10, pp. 573–575, 1990.

[2] C. McGarrity, Y. N. Ning, J. L. Santos, and D. A. Jackson, "A fiber optic system for three phase current sensing using a hybrid sensing technique," *Review of Scientific Instruments*, vol. 63, no. 3, pp. 2035–2039, 1992.

[3] J. L. Santos, F. Farahi, T. P. Newson, and D. A. Jackson, "Time division multiplexing of optical fiber sensors with sampled modulation of laser diode," *Optics Communications*, vol. 78, no. 2, pp. 143–148, 1990.

[4] J. L. Santos, F. Farahi, T. P. Newson, A. P. Leite, and D. A. Jackson, "Multiplexing of remote all fiber Michelson interferometers with lead insensitivity," *Journal of Lightwave Technology*, vol. 10, no. 3, pp. 853–863, 1992.

[5] J. L. Santos and D. A. Jackson, "Coherence sensing of time addressed optical fiber sensors illuminated by a multimode laser diode," *Applied Optics*, vol. 30, no. 34, pp. 5068–5076, 1991.

[6] J. L. Santos, A. P. Leite, "Multiplexing of polarimetric sensors addressed in coherence," presented at *9th International Conference on Optical Fiber Sensors (OFSS'9)*, Florenca, Italy, May 4–6, 1993.

[7] J. L. Santos and D. A. Jackson, "Passive demodulation of miniature fiber optic based interferometric sensors using a time multiplexing technique," *Optics Letters*, vol. 16, no. 15, pp. 210–1212, 1991.

[8] J. L. Santos, A. P. Leite, and D A Jackson, "Optical fiber sensing with a low-finesse Fabry-Perot cavity," *Applied Optics*, vol. 31, no. 34, pp. 7361–7366, 1992.

[9] A. B. Lobo Ribeiro, J. L. Santos, and D. A. Jackson, "Large range coehrence tuned Fiber optic interferometric system for application in accelerometers," *Review Scientific Instruments*, vol. 63, no. 7, pp. 3586–3589, 1992.

[10] A. B. Lobo Ribeiro and D. A. Jackson, "Low coherence fiber optic system for remote sensors illuminated by 1.3 μm multimode laser diode," *Review Scientific Instruments*, vol. 64, no. 10, pp. 2974–2977, 1993.

[11] D. A. Jackson, A. B. Lobo Ribeiro, L. Reekie, and J. L. Archambault, "Simple multiplexing scheme for fiber optic grating sensor network," *Optics Letters*, vol. 18, no. 14, pp. 1192–1194, 1993.

[12] G. P. Brady, S. Hope, A. B. Lobo Ribeiro, D. J. Webb, L. Reekie, J. L. Archambault, and D. A. Jackson, "Demultiplexing of fiber Bragg grating temperature and strain sensors," *Optics Communications*, vol. 111, no. 1–2, pp. 51–54, 1994.

[13] Y. J. Rao, A. B. Lobo Ribeiro, D. A. Jackson, L. Zhang, and I. Bennion, "Combined spatial and time division multiplexing scheme for fiber gratings sensors with drift-compensated phase-sensitive detection," *Optics Letters*, vol. 20, no. 20, pp. 2149–2151, 1995.

[14] Y. J. Rao, A. B. Lobo Ribeiro, L. Zhang, I. Bennion, and D. A. Jackson, "Simultaneous spatial, time and wavelength division multiplexed in-fiber grating sensing network," *Optics Communications*, vol. 125, no. 5–6, pp. 53–58, 1996.

[15] J. M. Baptista, P. M. Cavaleiro, and J. L. Santos, "Self-referencing intensity based *Q*-type fiber optic sensor," *Journal of Optoelectronics*, vol. 10, no. 105, pp. 105–113, 1995.

[16] J. M. Baptista, J. L. Santos, and A. S. Lage, "Mach-Zehnder and Michelson topologies for self-Referencing fiber optic intensity sensors," *Optical Engineering*, vol. 39, no. 6, pp. 1636–1644, 2000.

[17] P. M. Cavaleiro, A. B. Lobo Ribeiro, and J. L. Santos, "Referencing technique for intensity-based sensors using fiber optic Bragg gratings," *Electronics Letters*, vol. 31, no. 5, pp. 392–394, 1995.

[18] S. Abad, F. M. Araújo, L. A. Ferreira, J. L. Santos, and M. Lopez-Amo, "Fiber Bragg grating based self-referencing technique for wavelength multiplexed intensity sensors," *Optics Letters*, vol. 27, no. 4, pp. 222–224, 2002.

[19] J. Montalvo, F. M. Araújo, L. A. Ferreira, C. Vásquez, and J. M. Baptista, "Electrical FIR filter with optical coefficients for self-referenced WDM intensity sensors," *IEEE hotonics Technology Letters*, vol. 20, no. 1, pp. 45–47, 2008.

[20] J. Montalvo, O. Frazão, J. L. Santos, C. Vásquez, and J. M. Baptista, "Radio-frequency self-referencing technique with enhanced sensitivity for coarse WDM fiber optic intensity sensors," *Journal of Lightwave Technology*, vol. 27, no. 5, pp. 475–482, 2009.

[21] R. H. Heredero, S. Martin, R. Fernandez de Caleya, A. B. Lobo Ribeiro, F. M. Araújo, L. A. Ferreira, J. L. Santos, and H. Guerrero, "A study of the optical properties of photopolymer Fabry-Pérot microcavities by a dual-wavelength fiber optic architecture," *Journal of Measurement Science and Technology*, vol. 13, no. 7, pp. 1094–1099, 2002.

[22] C. Jauregui, F. M. Araújo, L. A. Ferreira, J. L. Santos, and J. M. López-Higuera, "Interrogation of low-finesse Fabry-Pérot cavities based on modulation of the transfer function of a wavelength division multiplexer," *Journal of Lightwave Technology*, vol. 19, no. 5, pp. 673–681, 2001.

[23] P. Caldas, P. A. S. Jorge, F. M. Araújo, L. A. Ferreira, M. B. Marques, G. Rego, and J. L. Santos, "Fiber modal Michelson interferometers with coherence addressing and heterodyne interrogation," *Optical Engineering*, vol. 47, no. 4, pp. 044401, 2008.

[24] O. Frazão, P. Caldas, F. M. Araújo, L. A. Ferreira, and J. L. Santos, "Optical flowmeter using a modal interferometer based on a single non-adiabatic fiber taper," *Optics Letters*, vol. 32, no. 14, pp. 1974–1976,

2007.

[25] L. A. Ferreira, E. V. Diatzikis, J. L. Santos, and F. Farahi. "Frequency modulated multimode laser diode for fiber Bragg grating sensors," *Journal of Lightwave Technology*, vol. 16, no. 9, pp. 1620–1630, 1998.

[26] F. M. Araújo, L. A. Ferreira, and J. L. Santos, "Simultaneous determination of curvature, plane of curvature and temperature using a miniaturized sensing head based on fiber Bragg gratings," *Applied Optics*, vol. 41, no. 13, pp. 2401–2407, 2002.

[27] O. Frazão, R. Romero, F. M. Araújo, L. A. Ferreira, and J. L. Santos, "Simultaneous measurement of temperature and strain using a step profile fiber Bragg grating arrangement," in *Proceedings Second Workshop on Optical Fiber Sensors*, Santander, Spain, June 9–11, pp. 36–39, 2004.

[28] G. Rego, P. V. S. Marques, H. M. Salgado, and J. L. Santos, "Arc-induced long-period gratings", *Fiber & Integrated Optics*, vol. 24, no. 3–4, pp. 245–259, 2005.

[29] O. Frazão, J. L. Santos, F. M. Araújo, and L. A. Ferreira, "Optical sensing with photonic crystal fibers (Invited Paper)," *Laser&Photonics Review*, vol. 2, no. 6, pp. 449–459, 2008

[30] O. Frazão, J. P. Carvalho, L. A. Ferreira, F. M. Araújo, and J. L. Santos, "Discrimination of strain and temperature using Bragg gratings in microstructured and standard optical fibers," *Measurement Science and Technology*, vol. 16, no. 10, pp. 2109–2113, 2005.

[31] O. Frazão, T. Martynkien, J. M. Baptista, J. L. Santos, W. Urbanczyk, and J. Wojcik, "Optical refractometer based on a birefringent Bragg grating written in a H-shaped fiber," *Optics Letters*, vol. 34, no. 1, pp. 76–78, 2009.

[32] O. Frazão, S. H. Aref, J. M. Baptista, J. L. Santos, H. Latifi, F. Farahi, J. Kobelke, and K. Schuster, "Fabry-Pérot cavity based on a suspended-core fiber for strain and temperature measurement," *IEEE Photonics Technology Letters*, vol. 21, no. 17, pp. 1229–1231, 2009.

[33] P. M. Cavaleiro, F. M. Araújo, and A. B. Lobo Ribeiro, "Metal-coated fiber Bragg grating sensor for electric current metering," *Electronics Letters*, vol. 34, no. 11, pp. 1133–1135, 1998.

[34] P. A. S. Jorge, P. Caldas, L. A. Ferreira, A. B. Lobo Ribeiro, J. L. Santos, and F. Farahi, "Electrical current metering with a dual interferometric configuration and serrodyne signal processing," *Journal of Measurement Science and Technology*, vol. 13, no. 2, pp. 533–538, 2002.

[35] S. Abad, F. M. Araújo, L. A. Ferreira, J. L. Santos, and M. Lopez-Amo, "Transparent network for hybrid multiplexing of fiber Bragg gratings and intensity-modulated fiber-optic sensors," *Applied Optics*, vol. 42, no. 25, pp. 5040–5045, 2003.

[36] A. B. Lobo Ribeiro, R. F. Caleya, and J. L. Santos, "Progressive ladder network topology combining interferometric and intensity fiber-optic-based sensors," *Applied Optics*, vol. 34, no. 28, pp. 6481–6488, 1995.

[37] A. B. Lobo Ribeiro, J. L. Santos, J. M. Baptista, L. A. Ferreira, F. M Araújo, and A. P. Leite, "Optical fiber sensor technology in Portugal (Invited Paper)," *Fiber & Integrated Optics*, vol. 24, no. 3–4, pp. 171–199, 2005.